SWIMMING SOUNDS AND THE SCHOOLING OF FISHES[1,2,3]

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This paper deals with the swimming sounds of some Bermuda fishes; it describes these sounds and relates them to the behavior of free fishes. E. V. Shishkova (1958a, 1958b) has recently published spectrograms of the sound produced by the movement of schools of scad (*Trachurus trachurus*, Carangidae) in the Black Sea. Such sounds are of interest in their possible significance to the behavior of fishes at sea, and as a reflection of fish behavior. The swimming sounds of fishes offer a possible means of control of fish school movements. The laughter which Hérubel derived (1912, p. 127) from the idea of controlling schools of herring is gradually fading. Sounds engendered by clupeids and the closely related engraulids are hitherto unreported, although a questionable account of herring sounds exists (Murray, 1831), and Maine fishermen describe sound stemming from large herring schools.

"Swimming sound" here conveys that collection of noises created in the water by movements of fish bodies, which characterize the movements of a given species. Such sound may stem from the rubbing together of skeletal parts, from the contraction of swimming muscles, or from water disturbed by various body movements. Shishkova refers to the swimming sound of *T. trachurus* as "hydrodynamic noise," which term she also applies to that noise caused by water flowing along a ship's hull; her data do not permit determining to what extent other events than water flowing over fish bodies contribute to the sound she describes. Since a similar criticism applies to my data, the more general term "swimming sound" seems preferable. Swimming sound is incidental to swimming and includes only those noises characteristically produced during swimming of a given species.

Listening equipment used in the investigation consisted of an AX-58-C Rochelle salt hydrophone and a Woods Hole Suitcase amplifier. Recordings were made during the summer of 1958 on a PT6-BN and a PT6BA2HZ Magnecorder tape recorder at $3\frac{3}{4}$, $7\frac{1}{2}$ and 15 inches/sec., and analyzed on a Kay Vibralyzer vibration frequency analyzer. Recordings were played back into the water with an Ekotape tape recorder Model 205, a Craftsman C550 amplifier and a QBG transducer. Recordings at sea were made from the motor launch ABUDEFDUF of the Bermuda Biological Station, Mr. Brunell Spurling, Captain.

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[2] Contribution No. 271 from the Bermuda Biological Station.

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SWIMMING SOUNDS OF SOME BERMUDA FISHES

Anchoviella choerostoma (Goode)—Hog-mouth fry. This small engraulid occurred in large and small schools on Bermuda shores during the summer of 1958. The schools were most commonly seen in shallow bays along the north shore of St. George's and Hamilton Islands where they are said to be driven by the commonly observed activity of predators (chiefly carangids and lutianids) feeding on the schools (B. Spurling, personal communication). *Menidia* (Atherinidae) is probably similarly driven on Long Island shores (Butner and Brattstrom, 1960). E. L. Mark (1905) described some Bermuda fishes as gathering schools of smaller fishes to lure prey for the former.

Once established in a bay, a school may remain for several days and even for weeks, gradually reducing in size under peripheral predation and the depredations of fishermen obtaining bait for which the fry are highly valued. A large school darkens the water so that it may be seen over a considerable distance, and the experienced Bermuda boatman can readily distinguish between that discoloration caused by a fish school and that due to rock formation and weed patches.

Observations on the behavior of a large school at sea, estimated to contain several million individuals, of *A. choerostoma* were obtained mainly in Bailey's Bay on August 7, 1958. The launch was repeatedly brought over the school which moved in and out relative to shore during recording. Recordings were obtained when the sea surface was calm and the only extraneous noise stemmed from the system and from snapping shrimp.

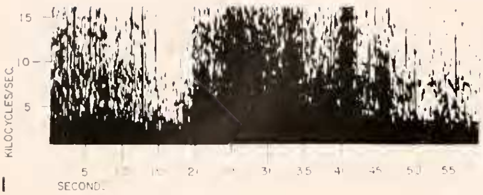
No predators were seen feeding during recording; activity around the borders of *A. choerostoma* schools on other occasions consisted of feeding by jacks (*Caranx* spp.) and pompano (*Trachinotus palometa*). Small *Caranx latus* (2 to 6 inches) were frequently netted with *A. choerostoma* and individuals were tolerated as members of small schools of the latter (up to 1000) maintained in the laboratory; the jacks fed on the host schools. *Jenkinsia* and *Sardinella* (Clupeidae) were also taken with *Anchoviella* on occasion.

For recording, the launch drifted over the Bailey's Bay school, engine off; although not obviously so, the behavior of the school was probably modified to some extent by the presence of the boat. During recording, the school was either lying at rest with individual fish turning slowly within a narrow circumference, or the

TABLE I

Characteristics of swimming sounds

Species	Size	Sound	Maximum frequency	Frequency of greatest intensity	Time duration
Anchoviella choerostoma	3 inches	Streaming	1.6 kc.	Below .5 kc.	Variable
		Veering of school	2 kc.	Below .8 kc.	.2–.6 sec.
Caranx latus	2–6 inches	Veering of individual	1.7 kc.	Below 1 kc.	.03 sec.
Caranx ruber	1 foot	Veering of individual	1.6 kc.	Below .7 kc.	.05 sec.
Trachinotus palometa	1 foot	Veering of individual	.7 kc.	Below .25 kc.	.06 sec.



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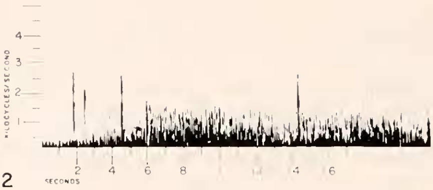

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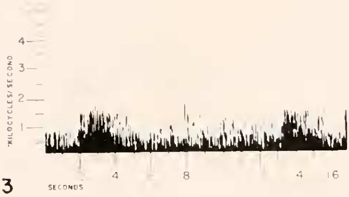

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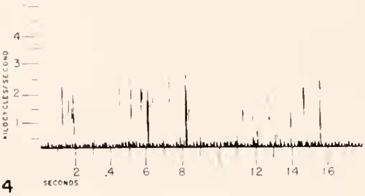

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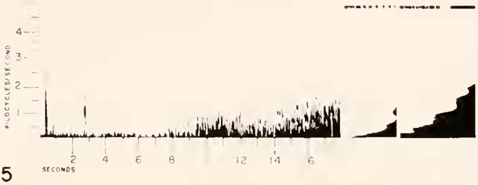

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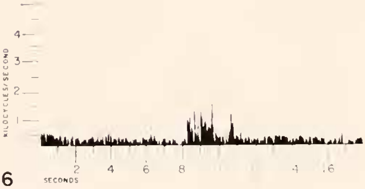

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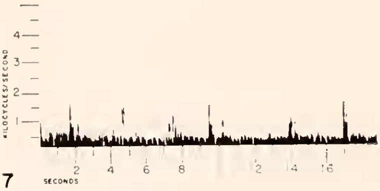

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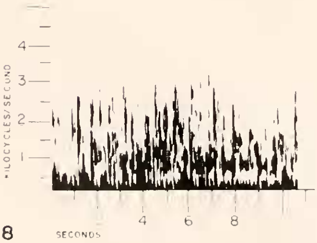

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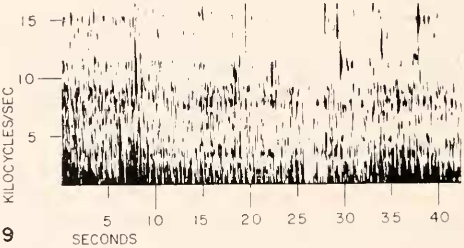

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FIGURE 1. Streaming, resting and veering of *Anchoviella choerostoma.*

FIGURE 2. Beginning of a streaming movement of *A. choerostoma.*

FIGURE 3. Two veerings during streaming of *A. choerostoma.*

FIGURE 4. Background and system noise during recording at sea in Bailey's Bay, August 7, 1958.

school had assumed a single direction and the fish were streaming around and by the hydrophone, or the school in the process of streaming suddenly veered in direction with a resultant sharp increase in sound intensity.

Sound could not be recorded from the school at rest; streaming and veering both produced considerable sound (Table 1). Sounds similar to these are aptly described by Shishkova (1958a) for *T. trachurus* as being like a pouring or a splash and like a rise and fall in system noise. The greater the degree of veering, the greater the intensity of its noise. The school streamed slowly and rapidly past the hydrophone; sound intensity fluctuated with variations in speed of movement of the school.

Suitcase amplifier and Magnecorder settings varied from 0 + 4–10 and 20–3 db, respectively, to 0 + 14–7 and 30–3 db during recording; at all settings, some veerings of the school overloaded the system.

The entire school covered approximately half an acre; during the observation period, the school broke occasionally into two or three smaller groups. The school and its subdivisions tended to disperse somewhat and gather closely again, so that concentration of fish varied. At times, the school appeared layered, a thinner upper stratum moving in a different direction than the lower bulk of the school. All recordings were done over sandy bottom while the school lay in 2 to 4 fathoms of water; the hydrophone was lowered to mid-depth of the school. When streaming, the school moved past the hydrophone leaving a circular area clear of fish, extending about 6 inches from the casing. With a casing of different color, this interval might be expected to vary (Breder, 1951).

When the school was at rest, it could be stimulated to move by the slightest flexing and stiffening of the observer's knees aboard the 21-foot launch when visual clues were excluded. The casting of a shadow over the school by hand and body movements did not cause this behavior. If the school were at rest when pressure was applied to the deck of the boat by the knee-bend method, it would begin to stream; if it were streaming, it would veer and usually alter the speed of swimming to some extent.

The lower portion (up to 1.5 kc.) of a frequency analysis of sounds stemming from a typical sequence of movements of the *Anchoviella* school is shown in Figure 1. During the 6 seconds of recording illustrated, the school came nearly to rest, began moving again at 2 seconds, veered a few times between 2 and 5 seconds, then quieted again. Abbreviated vertical streaks in the background are due to snapping shrimp; some system noise is indicated below .25 kc.

A similar sequence of events is shown in Figure 2 over a broader frequency scale (5 kc.) and briefer time interval (1.7 seconds). Here the beginning of a streaming movement is shown, again with a few snapping shrimp spectra in the background. Figure 3 shows the spectra of two veerings of the school during a streaming movement. In each of these records, there has been sufficient attenua-

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FIGURE 5. Sections through spectrum of recording of *A. chocrostoma* school while at rest and while streaming.

FIGURE 6. Veering of *Caranx latus* school.

FIGURE 7. Feeding and swimming sounds of *Caranx latus*.

FIGURE 8. Veering of *Caranx ruber*.

FIGURE 9. Veering of *Trachinotus palometa*.

tion to bring the schooling movements clearly into the foreground. In Figure 4, the ambient underwater sound of the area (mainly snapping shrimp) and system noise is shown after the *Anchoviella* school had moved inshore from the launch on one occasion.

Figure 5 shows sound intensity spectra (sections) during a recording made from the school at rest and after it had begun to stream. The first section was taken at .6 second of the time scale (school at rest), and the other at 1.3 seconds (school streaming). These sections provide a qualitative indication of the amount of sound stemming from a streaming movement at various frequencies at a point in time. Swimming sound of another *Anchoviella* school of considerably smaller dimensions could not be separated from background noise, due mainly to wave action during a moderate sea state with the equipment employed. In summary, *Anchoviella* swimming sound lies mainly below 2 kc. (Table I). Veering of the school introduces sharp intensity increases of between .2 and .6 second duration.

Attempts failed to record the swimming sound of *Anchoviella* in the laboratory from groups of 500 to 1000 individuals; the sound did not rise above extraneous noise. These experiments were performed in a cement tank, the fish being confined by a wood and plastic screen to an area 8 feet × 2 feet × 1 foot deep. The AX-58-C hydrophone was placed across the tank and fish driven around it. This paper presents evidence that the swimming activity of even small groups of *Anchoviella* is probably important in maintaining the coherence of the school; the swimming sound of a large school is one component of this activity.

A school of blue-fry (*Atherina harringtonensis*, Atherinidae) passing slowly under the launch on August 7 near Bay Island in Bailey's Bay did not respond to the knee-bend method successful in stimulating streaming and veering in *Anchoviella*. The blue-fry school was in the form of a compact ball of perhaps 1000 fish, each turning in its own particular pathway within the school as the latter passed beneath the boat. No swimming sound could be detected.

Caranx latus Agassiz and *C. ruber* (Bloch)—Yellow Jack and Skip Jack. These carangids, common in Bermuda, feed voraciously on *Anchoviella* as well as on other fishes. The *C. latus*, from 2 to 6 inches in length, were captured in small numbers with *Anchoviella* and separately off the dock of the Bermuda Biological Station. Observations are based mainly on aquarium experiments. Two large impounded schools of adult *Caranx ruber* were recorded on the west side of Coney Island on June 26 and August 6, 1958, through the kindness of a commercial fisherman (Mr. Spurling, Senior), and a third school was recorded during underwater listening in Castle Roads on July 11.

Since pharyngeal tooth stridulation may accompany the swimming sound of *Caranx* spp., this habit bears comment. Pharyngeal tooth stridulation of *Caranx hippos* has been described (Burkenroad, 1931; Fish, 1948; Moulton, 1958), and Fish (1948, 1954) describes the stridulating sounds of a number of other carangids. The pharyngeal tooth stridulation is produced more readily by young jacks hand-held gently under water (*C. latus*, *C. hippos*) than by adult jacks so treated (Moulton, 1958, p. 364); it was recorded at Bermuda from adult *C. ruber* held next to the hydroprone in an impounded school, and by *C. crysos* speared off Nonsuch Island on August 17.

Several attempts failed to elicit pharyngeal tooth stridulation from adult pompano (*Trachinotus palometa,* Carangidae) and *Calamus bajanado* (blue-bone porgy, Sparidae), both of which are equipped with formidable pharyngeal teeth. Adult grunts (*Haemulon sciurus,* Pomadasyidae) of some species, on the other hand, stridulate readily when similarly treated.

The present account deals mainly with the thumping sound produced by veering of *Caranx* spp., but pharyngeal tooth stridulation is also produced at times during this maneuver.

Several small groups (from 12 to 20) of young *C. latus* were confined in aquaria 1½ feet × 1¼ feet × 1 foot deep with the hydrophone. Undisturbed, these fish milled about the aquarium equidistant from each other, each on its own pathway. When a hand was flicked at the aquarium or a stick poked into the water, the small group of jacks became at once a tightly coherent school, streaming about the aquarium and veering on repetitive stimuli as had the *Anchoviella* at sea. Streaming did not introduce sound detectable above background; veering did. This movement even of individual fish resulted in distinct thumps similar to those described by Fish (1954) from shocked *C. crysos* (7.75 mm.?). When stemming from a group of *C. latus,* the thumps occurred in volleys (Fig. 6, Table I).

During feeding on bits of meat, the *C. latus* dispersed through the aquarium. The thumps then became scattered as individuals darted for food, and were accompanied by occasional sounds of the stridulation of teeth (Fig. 7).

During the Coney Island recordings, the hydrophone was hung in the midst of schools of *C. ruber* before and during raising of the net. Veering of the fish about the hydrophone caused volleys of thump-like sounds similar to those of *C. latus,* but somewhat deeper in predominant tone (Fig. 8, Table I). Swimming sound engendered by streaming movements was also detected in these recordings and that obtained at Castle Roads.

Trachinotus palometa Regan—Gaff-topsail Pompano. The swimming sound of two pompano approximately 1 foot long was recorded in the cement tank. The animals were not fed during recording. Only thumps coincident with veering occasioned by sudden hand movements in the water were recorded. Sound spectrograms of two flurries of activity are illustrated (Fig. 9, Table I).

Diplodus argenteus (C. and V.)—Bream. Attempts failed to record a swimming sound from 6 of these fish (Sparidae) approximately 8 inches long in a Station aquarium. The only sound detected was made by the fish bumping against the sides and bottom of the tank as a probe was moved gently about the aquarium. These sounds are not clear and sharp like carangid thumps; they are variable and random and are not clearly correlated with describable behavioral phenomena.

Various spear fishermen at Bermuda during 1958, including reliable observers from the Station, reported hearing sounds underwater produced during evasive swimming of grouper (Serranidae) and parrotfish (Scaridae), "any large fish," and hogfish (*Lachnolaimus maximus,* Labridae), as well as grunts of the hamlet or Nassau grouper (*Epinephalus striatus*) and volleys of squirrelfish (*Holocentrus ascensionis*) sound (Moulton, 1958).

THE PLAYBACK OF UNDERWATER SOUND TO FISH SCHOOLS

The playback of underwater sound has been useful in modifying fish behavior (Moulton, 1956a, 1956b; Tavolga, 1956, 1958). The habit of *Caranx* of feeding on *Anchoviella* led to playing back to the *Anchoviella* school recorded on August 7 recordings of the stridulation sound of *C. latus* and of the swimming sound which accompanies its feeding. The transducer was lowered to mid-school level. The *Anchoviella* cleared the area beneath the launch more quickly during this playback than during recording. Further, during sound playback, the school showed a greater tendency to divide than during recording.

A collateral observation is of interest: When playback began of the stridulation sound at sea, an adult barracuda (*Sphyraena barracuda,* Sphyraenidae) came abruptly to a spot about 8 feet from the suspended transducer and lay quietly facing it for about three minutes. This behavior was unique to all observers, including Mr. Spurling, an experienced Bermuda fisherman and boat captain. (Mr. Spurling's comment: "I've never seen a barracuda act like that before.")

Stridulating sounds and thumps of young *C. latus* played back to about 500 *Anchoviella* in the Station cement tank were accompanied by quickened swimming and milling which gradually subsided. Approximately one-fourth of the fry moved to the opposite end of the tank over and under a horizontally suspended hydrophone which they did not pass spontaneously before sound transmission, and during hand movements in the tank.

Playback to the impounded school of *C. ruber* recorded at Coney Island on August 6, as it milled within the net, of a series of pharyngeal tooth stridulations of *C. latus* recorded in Station aquaria, initially was accompanied by an immediate movement of the school to the far end of the net. After some minutes of playback, the school failed to respond to these sounds and to feeding sounds. These sounds were listened to by surface divers and sounded like the amplified sounds heard during recording.

After the swimming sound of the large school of *Anchoviella* had been recorded at sea on August 7, the recording was played back into an aquarium containing young *C. latus.* The latter showed quickened swimming movements of a nondirectional type. It has already been mentioned that small *C. latus* may join *Anchoviella* schools, feeding on the members of the school; they may be attracted to the school by its swimming sound.

Pharyngeal tooth rasps played back to the source species (*C. latus*) in a Station aquarium on August 1 appeared to initiate feeding reaction. The fish became exceedingly active, swimming about furiously, and facing the transducer to nibble at its rubber surface. After several minutes the activity subsided and the fish swam about as usual.

SWIMMING MOVEMENTS AND SCHOOLING BEHAVIOR OF CARANX AND ANCHOVIELLA

The normal behavior of schooling fishes. Caranx, Trachinotus, and *Anchoviella* are truly schooling fishes, and whether at sea or in aquaria, groups of these fishes form cohesive schools. Their behavior bears examination as it relates to factors maintaining the school at sea.

When adult pompano attacked *Anchoviella* schools at sea, the former were in compact school formation, and usually swam directly through the school of fry; feeding of *Caranx crysos* at the periphery of a school was characterized by irregular darting movements and swift swimming of individual jacks.

At rest in aquaria and at sea, the *Anchoviella* school is clearly outlined, although individuals take independent pathways within the school in daytime as at night. When the school is streaming, and when a schooling fish (*Menidia menidia*) of the Woods Hole area is subjected to a tidal current in a live car, these fishes line up parallel to each other and veer together upon appropriate stimulus.

The importance of water currents in mediating behavior of fishes is further underlined by the behavior of small amberjack (2-inch *Seriola* sp., Carangidae) lurking under sargassum weed clumps southeast of Bermuda on August 18. The fish abandoned each clump as the 65-foot *Panulirus* drifted down upon it, and swam directly to another clump, often some yards away but always along the same line of weed and thus within the same convergent zone (Woodcock, 1944, 1950). Due to a combination of factors, significantly wind and Coriolis force, sargassum weed in the open sea tends to arrange itself in parallel rows, the rows being spaced at quite regular intervals under a given set of conditions, and parallel to wind direction (Woodcock, 1944, 1950). Water currents, probably even micro-currents, are of great importance in the open sea in determining the distribution of fishes (see Hasler, 1956); persistent sensory orientation to a particular current or moving body of water may be of considerable importance in maintaining not only the position but also the cohesiveness of fish schools, particularly through hours of darkness (Moulton, 1957a).

Members of a single school vary in their behavior. Schools of 500 to 1000 *Anchoviella* in the cement tank tended to divide at rest into two or three smaller groups; one group was usually markedly larger than the other(s). These groups, treated alike from capture, differed in sensitivity to stimuli; some were easily frightened, others held their position in the face of a variety of stimuli (*e.g.*, a prodding stick or hand).

In a study of variation in reactions to stimuli, a plastic screen confined a single school of about 1000 *Anchoviella* to an 8-foot section of the cement tank during attempts to record swimming sound. The hydrophone was placed across the tank, 3½ feet from the end containing the fish. During transmission of jack stridulation recordings in the area containing the fish, approximately one-fourth of the school moved past the hydrophone. Pushing down on a small board floating over the school (in simulation of the knee-bend method) caused approximately one-half the remaining fish to pass the hydrophone. Then a hand was waved vigorously in the water with the balance of the school; a recalcitrant two dozen fish still remained in the smaller portion of the tank, gathered in a cohesive school.

Young *Caranx latus* tend to school with *Anchoviella;* in an aquarium, a school of 12 of the former formed a tight formation immediately above the back of a 10-inch squirrelfish (*Holocentrus ascensionis*, Holocentridae). They turned with the squirrelfish as it moved slowly about the tank; the latter made no move toward the jacks. Another group of 20 *C. latus* was confined for several hours in an aquarium with an adult spiny lobster (*Panulirus argus*). So long as they were contained together, night and day, the *C. latus* remained at the top of the tank in a tight school. The spiny lobster was removed one night under artificial light, and at once the 20 jacks dispersed over the bottom of the aquarium and assumed a striking striped pattern completely unlike their usual drab coloration.

Experiments on blinded fish. In order to examine factors other than vision mediating the schooling of fish, adult *Anchoviella* were blinded by bilateral eye removal under anaesthesia (MS222 1:3000, Sandoz Pharmaceuticals) and allowed to recover, or became blinded through eye loss in a syndrome developing within hours of capture in a school held in the cement tank. On successive trials, a blind individual was placed in an aquarium with 12 normal individuals. When the latter were at rest, individuals milling slowly about, the blinded individuals swam through the group and about the aquarium generally until reaching the side of the tank, then took up new headings; they did not orient to the normal fish.

If the normal fish were startled by a hand movement next to the aquarium, they streamed and veered as did large schools at sea; at such times, the blinded individual immediately joined the normal fish in school formation and behaved as did the latter. Similarly, in the cement tank, blinded *Anchoviella* moved with the larger group of normal fish during streaming movements. When the normal fish came to rest again, blinded individuals returned to random movements, while even at rest the normal fish maintained approximately equal intervals between individuals. Isolated blinded fish did not respond to hand movements adjacent to the aquarium.

Unilaterally blinded *Anchoviella* maintained position with the normal fish when the latter were within the field of vision. This latter observation is in agreement with observations obtained on *Menidia* behavior at Woods Hole in 1957, where the experiments were performed in a live car suspended from a raft in Great Harbor; bilaterally blinded fish swam directly through groups of normal fish at rest and oriented independently of normal fish in currents flowing through the live car, while unilaterally blinded specimens maintained position with schools located at least in part on the side of the unoperated eye (Moulton, 1957a).

While movements of the individual members of the fish school are important in maintaining the remarkable integrity of the school, the members of the school are probably sensitive to pressure waves created by the school and probably orient to these waves; the movements of the school as a whole are probably important in maintaining its own integration.

Anchoviella did not disperse through the cement tank after dark as *Jenkinsia* (Breder, 1951) and chub mackerel—*Scomber colias*, Scombridae (Shlaifer, 1942) —do in aquaria. Schools of 500 to 1000 were in tight formation in the center of the cement tank in resting behavior during several examination periods on dark nights when an electric light was turned on, and behavior did not change notably with the light; the basement-located tank was too dark on moonless nights for me to see the fish in it.

C. latus in small numbers confined alone in darkness for several hours did not noticeably change their distribution when a light was turned on. Neither *C. latus* nor *Anchoviella* seems to depend so markedly on light for schooling formation as apparently do *Jenkinsia* and *Scomber*.

A Ghana Fishery Depending on Swimming Sound

A. P. Brown, in an anthropological account of the fishing industry of the Labadi District of the Gold Coast (Irvine, 1947, p. 25), mentioned the three-pronged paddles found in the sea-going canoes of the Coast, without indication as to their use. Inquiry was made subsequent to a United Nations news release suggesting an application to the fisheries.

The paddle, for possession of one of which I am indebted to Mr. D. A. Hammond of the Fisheries Department, Accra, is in typical form 4 feet 9 inches in length with a handle 1¾ inches in diameter. The foot-long flattened blade terminates in three broad, blunt teeth, comprising 4½ inches of the blade length, each approximately 2 inches in width at the base, the center one tapering slightly more than the other two. Mr. Hammond describes the use of this paddle as follows:

"The use of the paddle as (a) hearing aid in fishing is well-known to our fishermen from Ada to Takoradi. It is particularly used by the herring fishermen. 'Herring' here refers to *Sardinella aurita* and *S. cameroonensis*. It is also used, however, to detect shoals of shad (*Ethmalosa dorsalis*), long-finned herring (*Ilisha melanota*) and cassava fish (*Cynoscion senegalla*). (Identifications from Irvine, 1947).

"Where there are no surface fish visible, the method is to place the broad part of the paddle in the water over the stern of the canoe, place the ear to the top of the handle, and rotate the paddle very slowly. Only skillful and experienced fishermen are appointed to do it. The face of the paddle acts as a sounding board and receives the vibrations which it transmits to the hearer. By rotating the paddle, the fisherman is able to get the direction of movement of the fish and from the intensity of the sound, he can judge how (distant) the fish (are). Those fish which move in large shoals—for example, herring or shad, as well as the large rocks in the sea, make distinct sounds. From the sound, the fisherman can tell whether it is a fish or rock. The sound of the herring is characteristic and never mistaken. This method is particularly successful in waters of 7 to 10 fathoms and between 11 P.M. and 3 A.M. Those paddles which are particularly good are treasured. Some of them are very old." A variety of the Ghana-type paddle is said to be used for a similar purpose in Liberia (Mr. William Watkins, personal communication).

Underwater listening occurs in various parts of the world as an important aspect of commercial fisheries (Cousteau, 1953; Kesteven, 1949; Marshall, 1954; Parry, 1954; Westenberg, 1953). It is likely that in the fishery described by Mr. Hammond, the swimming sound of the clupeids (sciaenids may produce other sounds) is conveyed by the three-pronged paddle to the fisherman's ear.

Discussion

The schooling behavior of teleosts probably depends primarily on vision in the daytime (Shlaifer, 1942; Breder, 1951). Yet schools of *Anchoviella, Clupea harengus* and other schooling fishes maintain their schools at sea through hours of darkness; herring fishermen depend on this fact in "lighting up" herring schools at night (Moulton and Backus, 1955). While it may be that light stemming from luminescent organisms and that of moon and stars on clear nights may afford sufficient stimulus to abet schooling at night, some conditions of darkness at sea undoubtedly preclude vision and require other stimuli as predominant in providing for maintenance of the fish school at night. Certainly other factors than vision enable blinded fish (*Anchoviella, Menidia*) to move with their respective schools.

The possible role of water currents in maintaining fish schools at sea has been briefly discussed.

Significant factors in low frequency sensitivity of teleosts are the lateral line and isolated cutaneous receptors (von Frisch, 1938; Griffin, 1950; Lowenstein, 1957). Tracy (1920a, 1920b) and others have suggested that the connection between air bladder and inner ear of clupeids (engraulids possess a similar connection—Berg, 1947) may be more important as a pressure control device related to gas physiology of the air bladder than to hearing facility. While it is not unlikely that the paired passages may serve in both capacities, the remarkable sensitivity of *Anchoviella*, as well as of some clupeids (Moulton and Backus, 1955; Moulton, 1956a), to pressure waves in the water is suggestive of special adaptations to reception of pressure changes.

Anchoviella are sensitive to very slight pressure waves in the water; the swimming sounds described fall within the frequency range of sensitivity of all fishes studied in this connection. It is now simply conjectural, although some supporting evidence has been presented, to suggest that the swimming sounds of various carangids and of *Anchoviella* furnish a mechanism in addition to water currents and visual sensitivity by which schools of fish at sea are maintained under a variety of circumstances. Either these sounds or the body movements from which they stem must be a primary factor.

The swimming sounds described are to a degree species-specific. Shlaifer (1942) observed that chub mackerel, pairs of which will school together, will not school with abnormally moving fish of the same species. Normal *Menidia* and *Anchoviella* do not arrange themselves in schooling formation with blinded individuals; the latter will school with the former. It is suggested that the fish school at sea is maintained by a number of factors, given the proper amounts of food and minimum predation: sensitivity to particular water currents and masses, vision, and the behavior of the school as a whole which acts an an acoustical core and as a wave pressure source to which individuals of the schooling species orient. It is suggested that the swimming sound is not simply a mechanical or accidental sound, but that it possesses biological significance. It is demonstrated that source species and other species may react to amplified swimming sound.

Another factor influencing the maintenance of the fish school is reflected in differential sensitivity of *Anchoviella* to increasingly dispersive stimuli. After a series of such stimuli, a core of recalcitrant individuals remains in the test area in an experimental tank, and may furnish the nucleus around which more sensitive members of the school fluctuate at sea; streaming and veering may orient around a group of relatively insensitive individuals forming an "anchor" to the school.

It is clear that the swimming sound of different species of schooling fishes (*Anchoviella, Caranx, Trachinotus*) varies in its characteristics with species as well as with size of the fishes concerned. Large schools of fishes as small as *Anchoviella* (about 3 inches) and as large as *Caranx ruber* (about 1 foot) introduce considerable sound into the water. This may in future be utilized in experiments on schooling fishes in waters less clear than those studied, to test influence of various stimuli on schooling fishes and to explore sensitivity to these stimuli. Although Shishkova (1958a) abandoned the hope of stemming acoustically the flow of anchovies from the Russian Sea of Azov into the Black Sea, and of masking ship noise with swimming sound, other possible uses of swimming sound exist; a likelihood is present that fishermen can control acoustically to some extent the movements of clupeid and engraulid schools.

The characteristics of these sounds are more like those of sounds produced under circumstances related to defensive behavior of fishes than of sounds produced under other circumstances (Moulton, 1957b). The sound attendant on veering may have some protective value. If this were true, large schools of herring and anchovies would be more resistant to predation by other fishes than would small schools. The joining of *Anchoviella* schools by young *C. latus* may be primarily protective for the latter; their feeding on the host school would simply indicate poor "guestmanship."

The swimming sounds described, as well as sound stemming from the movement of any large fish in the sea, are probably due to a number of factors; hydrodynamic noise, to which Shishkova relates all of the sound, skeletal movements, and contraction of axial musculature during strong swimming movements against a gas-filled, resonating air bladder. None of the sounds described are continuous even during steady streaming movements, indicating that they stem from the bodies of individual fishes during muscle contraction, rather than from the hydrodynamic effects of continuous water flow around fish bodies.

All of the swimming sounds studied lie below 2 kc., and thus are of lower frequencies than many sounds created by fishes by organs apparently specialized for sound production (Moulton, 1958). These results differ from those of Shishkova (1958b) who found components of *T. trachurus* swimming sound at 16 kc. (It seems likely that her fish were chewing or stridulating during recording.) The frequency span of greatest intensity of swimming sound, as indicated by darkening of vibragrams, is lower for large fish than for small (Table I).

After submission of the manuscript of this paper for publication, the author's attention was called to a recent extensive study of social groupings in fishes by Breder (1959). Of special pertinence to the present work is Breder's caution that the responses of members of a fish school to light and darkness will vary with individuals, and that light exposure which fish have received earlier will be of great importance.

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SUMMARY

1. The swimming sounds of four schooling species of Bermuda fishes are described. The sounds stem from streaming and veering of schools at sea.

2. Responses of schooling species to playback of sounds stemming from schools are described. Exploitation of these responses in experimental and commercial fishing is suggested.

3. On the basis of observation at sea and of laboratory experiments, mechanisms useful in maintaining formation of schools at sea are discussed. These include vision, water currents and pressure waves initiated by the movements of fish bodies and the sounds they engender.

4. An African acoustical fishery, probably relying on the swimming sounds of fishes, is described.

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